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# The Case for Microreactors in Australia

***June 2024***

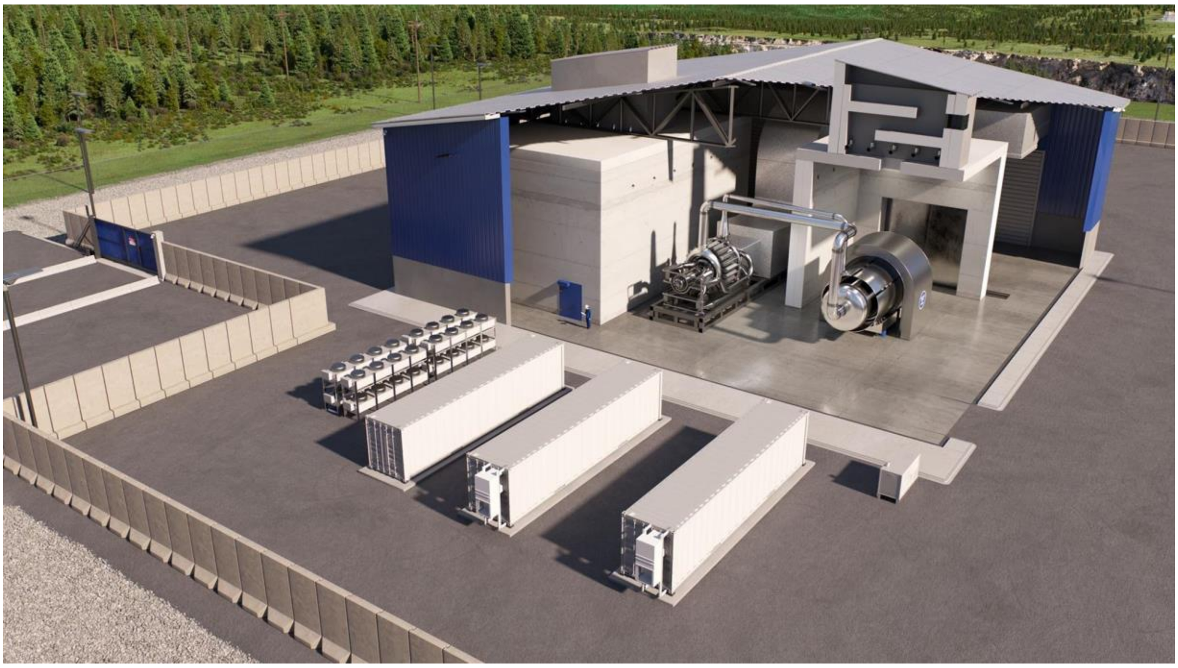


Image: Westinghouse eVinci microreactor

## EXECUTIVE SUMMARY

**Microreactors are essentially "nuclear batteries".**

**Microreactors are of unique potential value in off-grid applications, most especially for the mining industry.**

**The deployment of microreactors for off-grid electrical and heat will enable a transition away from diesel to low emissions, reliable nuclear supply for off-grid mining sites, other industries, critical infrastructure, energy-intensive operations like data centres and remote communities.**

**ANSTO's OPAL reactor at Lucas Heights has a thermal power capacity of 20 MW. Power reactors are banned under Australian law, but the OPAL reactor was licensed to operate as a research reactor.**

**Many microreactor designs have a lower thermal power than OPAL but are not allowed to be licensed because they are classed as "power reactors". If the law were to be changed these microreactors could provide essential services to Australian industry by replacing the high emissions from the use of diesel power.**

**Subject to regulatory approval, microreactors will provide Australian companies with versatility and diversity in their future development.**

**Microreactors are designed to be inherently safe.**

**Microreactors are likely to join SMRs in contributing to the reduction of Australia's greenhouse gas emissions.**

## 1. What are microreactors?

Microreactors are essentially “nuclear batteries” designed to be competitive with diesel in off-grid applications. Large power reactors being deployed today have an average electrical output of 1,100 MWe which would supply about 1 million households. They are too large for small grid systems or off-grid applications.

Because there is a need for low emissions electrical supply for smaller applications, Small Modular Reactors (SMRs) are being developed. These have an electrical output of up to 300 MWe. A form of SMRs has been deployed for many years in nuclear-powered submarines.

Even 300 MWe is too large for many off-grid applications and there is a growing interest in even smaller reactors with an electrical output of up to 10 MWe. These are commonly known as Micro Modular Reactors (MMRs) or simply microreactors.

## 2. Advantages of microreactors

The small physical size of a microreactor enables transport to site in shipping containers and quick on-site installation.

Microreactors can be designed to supply any combination of electrical supply and process heat.

Microreactors have many advantages:

- Provide reliable, low emissions power in remote locations or for small grid systems
- Compact, factory built transportable module reducing on-site installation time and reducing the risk of delays
- Quick on-site installation – months/weeks instead of years
- Scalable – modules can be added to meet demand
- Load following capabilities, simple to operate and maintain
- Natural convection cooling of the reactor core
- Multipurpose – electricity + process heat + desalination
- Very compact, transport in shipping containers
- Very high level of passive or inherent safety – without the need for operator action or external electrical or water supplies
- Designed for a longer core life
- Can be used in emergency response scenarios to help restore power after disasters have damaged the normal electricity supply
- Work with renewable energies in a microgrid

## 3. Technological Development

The majority of large reactors and many SMRs are based on light water reactor technology. Light water SMRs have an operating temperature of <300°C at the steam turbine inlet giving a thermal efficiency around 33%. The 300°C steam temperature limits their applications for process heat. There has been a developing interest in advanced reactors operating at higher temperatures with therefore greater thermal efficiency and providing more opportunities for process heat. These are classed as *Generation IV* reactors. The research and development for their deployment is mainly driven by the *Generation IV International Forum (GIF)*, which has 13 member countries with major nuclear power programs led by the

USA, plus Australia since 2016. Australia was invited to join GIF because of ANSTO's international reputation as a nuclear research organisation, particularly in the area of advanced nuclear materials.

In the USA, Idaho National Laboratories (INL) and the National Reactor Innovation Centre (NRIC) are enabling developers by providing technical resources, capabilities and a demonstration site.  The US Federal Government is supporting development through funding and legislation. The US advanced reactor industry is developing several microreactor concepts and designs.

The Experimental Breeder Reactor II (EBR II) operated on the Idaho National Laboratory (INL) site from 1964-1994. Although the reactor has been decommissioned, the large concrete and steel containment dome has been retained. The dome is about 24m in diameter and 14m tall built of 1-inchthick steel plating with a reinforced concrete structure. The DOE had the brilliant idea to repurpose the containment to test microreactors. The Demonstration of Microreactor Experiments (DOME) test bed is a demonstration platform that can test four to five advanced reactors, up to 20 MWt that use HALEU. It will allow safety-significant confinement for reactors to go critical for the first time. The facility will speed up microreactor development and save companies money in the testing process.

In October 2023 the DOE selected Westinghouse, Radiant Nuclear and Ultra Safe Nuclear Corp. (USNC) to conduct the first experiments at DOME.

## 4. The high temperature gas reactor and TRISO fuel

One advanced reactor design that is very suitable for SMRs, including microreactors, is the High Temperature Gas Reactor (HTGR).

The HTGR is graphited moderated, helium cooled and is capable of operating at up to 900$^{o}$C which would enable its use for most process heat applications and high efficiency electricity generation. The key advantage is the TRISO (TRi-structural ISOtropic) particle fuel. This consists of a very small uranium particle, <1mm diameter, surrounded by three layers of carbon- and ceramic-based materials that prevent the release of radioactive fission products. The particles are assembled into cylindrical blocks or billiard ball size pebbles. This fuel is safe to >1800$^{0}$C and cannot melt in a HTGR.

TRISO fuel – Half a mm diameter uranium fuel kernel coated typically with 92 µm porous carbon buffer + 38 µm inner pyrolytic carbon + 33 µm silicon carbide barrier + 41 µm outer pyrolytic carbon to give < 1mm diameter coated particle.

TRISO fuel typically contains HALEU (High Assay Low Enriched Uranium), 5%-20% enriched in the fissile uranium isotope U-235. Natural uranium as mined contains 0.7% U-235, typical large reactors and water cooled SMRs use uranium enriched to <5%.

## 5. Heat technology

As an alternative to helium gas for heat transfer from the reactor core, the heat in some designs is transferred from the reactor fuel to the power convertor by heat pipes.

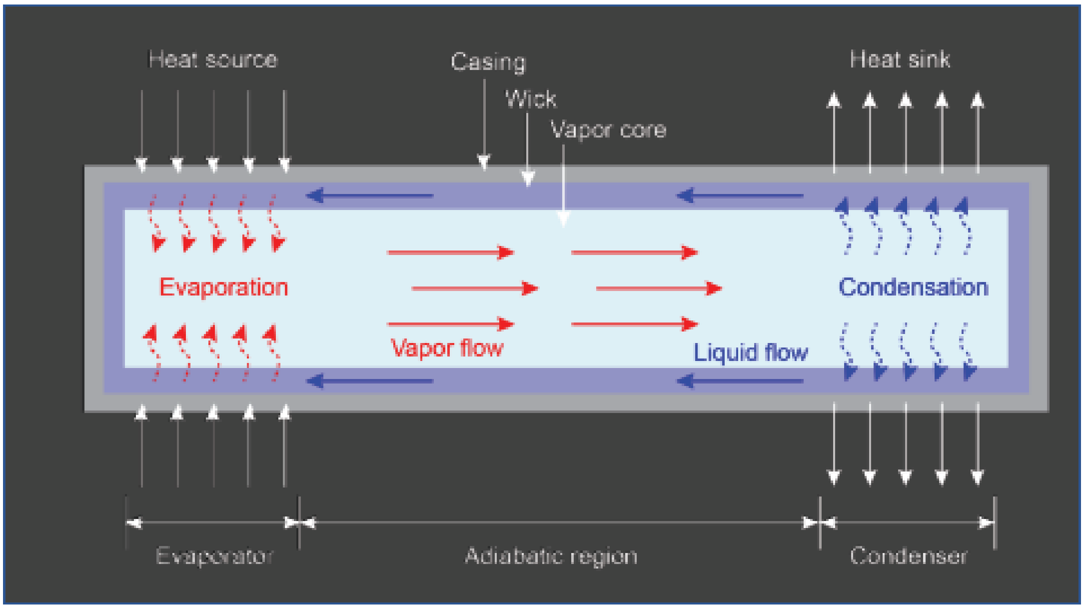



*Image: Oklo*

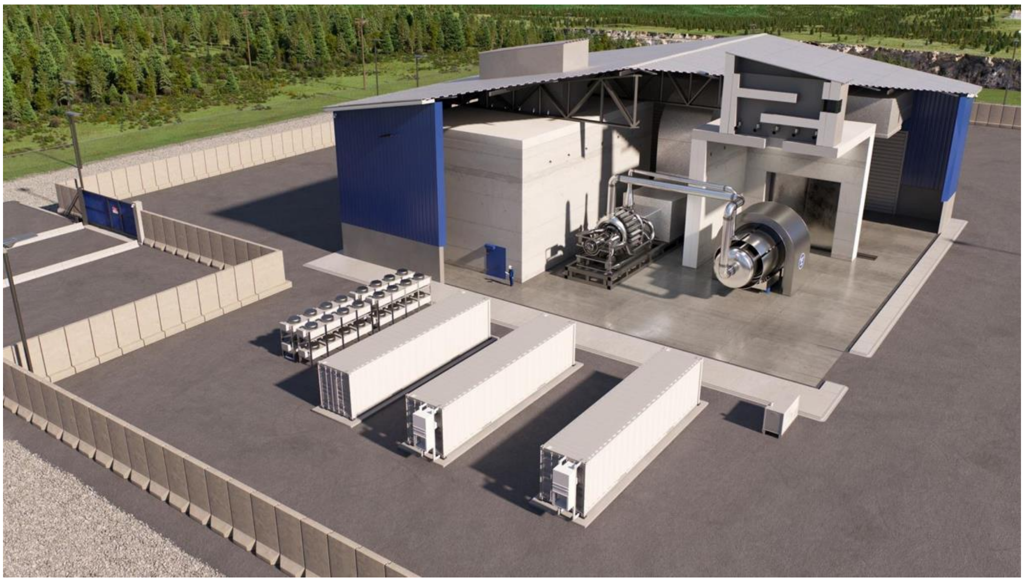
Heat pipes have been developed since 1994 at the Los Alamos National Laboratory (LANL) as a robust and low technical risk system with no moving parts and an emphasis on high reliability and safety. Originally developed for space applications, heat pipes are used in many microreactors. The heat pipe is filled with sodium or potassium and sealed. The vapor pressure over the hot liquid working fluid at the hot end of the pipe is higher than the equilibrium vapor pressure over the condensing working fluid at the cooler end of the pipe, and this pressure difference drives a rapid mass transfer to the condensing end where the excess vapor condenses, releases its latent heat. The condensed working fluid transfers back to the hot end by capillary action.

## 6. Competing microreactor technologies

### 6.1 Westinghouse eVinci Microreactor

Westinghouse have been designing and supplying nuclear reactors since the 1950's. Their current portfolio includes the AP-1000 large nuclear power reactor (3,400 MW thermal, 1250 MW electrical). AP-1000 reactors are operating in China and the USA. In 2023 they launched their SMR version, the AP300 (990 MW thermal, 300 MW electrical). They also have a microreactor size reactor named eVinci.

The eVinci microreactor has a nominal capability of 14 MWt / 5 MWe and can deliver 750$^0$C process heat. The plant is fully assembled at the manufacturing facility and arrives on site in three shipping containers – Reactor Container, Power Conversion Container and Instrument & Controls Container - and can be in operation in 30 days on a prepared basemat. It has a design life of 40 years and can be transported to a new site before end-of-life. The reactor is a solid monolithic block with three types of channels accommodating TRISO fuel, neutron moderator and sodium filled heat pipes. The are no moving parts in the primary cooling system. The plant is capable of autonomous operation and remote monitoring. The power conversion is by an air Brayton cycle. Refuelling every 8 years.



*A feasibility study by Bruce Power and Westinghouse in 2021 found that the EVinci microreactor could provide cost-effective energy to off-grid markets in Canada.*[1]

*Image: Westinghouse*

[1] https://www.brucepower.com/wp-content/uploads/2021/10/210283A_WestinghouseBPMicroReactor_ExecutiveSummary_R000.pdf

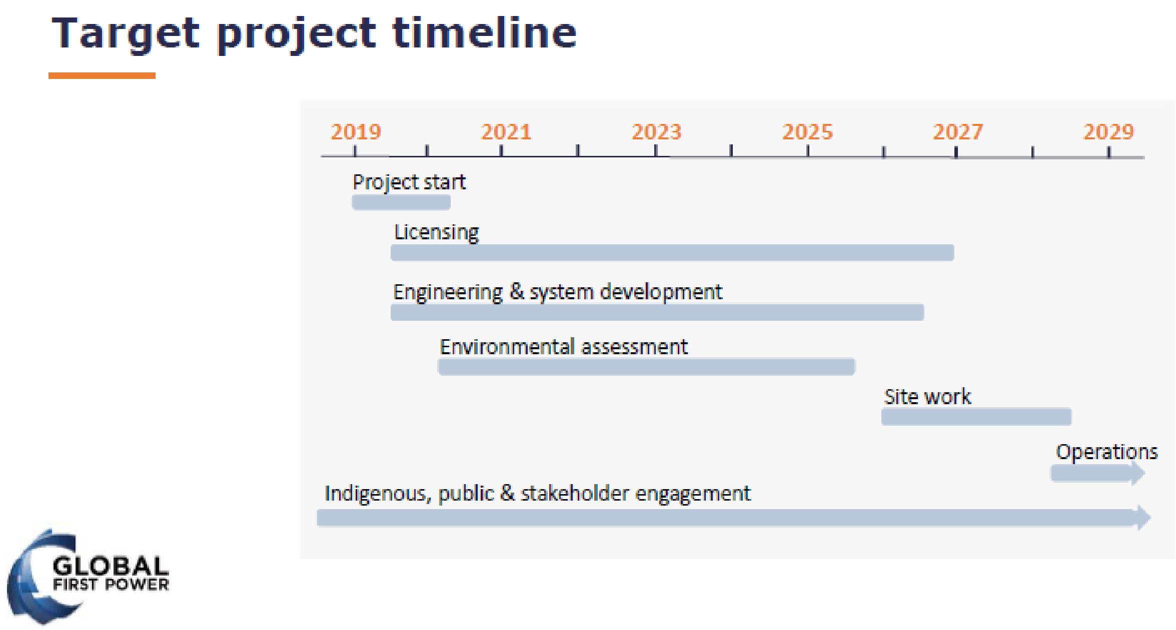
## 6.2 Ultra Safe Nuclear Corporation (USNC) Seattle USA microreactor

This microreactor is a high temperature gas cooled reactor with a 10 - 45 MW thermal output and an electrical output of 3.3 MWe -15 MWe using TRISO fuel and helium coolant.

Global First Power (GFP) is a joint venture between USNC and Ontario Power Generation (OPG) to site a demonstration MMR at Canada National Laboratory Chalk River site with target operation by 2028. The nuclear plant will supply 45 MWt of process heat to an adjacent non-nuclear plant by an intermediate molten salt heat exchanger. The heat can be used as process heat and to generate electricity. The fuel is a further development of TRISO that envelops TRISO in a Fully Ceramic Micro encapsulated (FCM) fuel which ensures containment of radioactivity during operations and accident conditions. The Project will demonstrate the commercial viability of the MMR technology to prospective customers (e.g., remote communities and mining industry). The design has a service life of 40 years and includes facilities for periodic refuelling on site. On site construction time is 18 months. The reactor can be ramped from idle 5% power to 100% in minutes.

The project is subject to Environmental Assessment (EA) in accordance with the *Canadian Environmental Assessment Act (CEAA 2012).* GFP has been preparing a draft EIS since 2021 and this will be submitted in 2024. Also in 2024, the Licence to prepare the site application will be submitted to the CSNC.

GFP estimate one microreactor could replace 1.2 billion litres of diesel.




*GFP Project update presentation 2023*

*Image: USNC*

USNC also have a project to deploy their MMR in the USA at the University of Illinois Urbane-Champaign.

In July 2023, USNC and its partner Jacobs was awarded USD29m though the UK Advanced Modular Reactor Research, Development and Demonstration program, with the aim of a USNC demonstration HTGR operating in the UK by the early 2030's.

## 6.3 BWX Technologies (USA) BANR microreactor

BWXT has 75 years' experience of nuclear technology in the USA, they have manufactured all the reactors for US naval propulsion.

BANR (BWXT Advanced Nuclear Reactor) is a TRISO-fueled High Temperature Gas Reactor (HTGR), graphite moderated, 50 MW thermal power scalable and is designed to be transportable in five ISO-compliant CONEX shipping containers. The fuel is 19.75% HALEU, with +5 years refuelling. BANR is designed with inherent and passive safety features.
In 2021, BWXT received an award of $111m over 7 years from the US DOE under the Advanced Reactor Demonstration program (ARDP).

In order to focus the design on a particular need, BWXT signed a 2 phase, 2 year contract with Wyoming Energy Authority (WEA) in September 2023. Phase 1 objective is to tailor the BANR design and commercial development plan to meet the needs of Wyoming, particularly trona (soda ash) mining. Also in September 2023 BWXT signed a co-operation agreement with Tata Chemicals to assess the viability of deploying BANR for their soda ash manufacturing operations in phase 2. Phase 1 of the WEA project is scheduled to be completed in May 2024 with a concept design for a lead site by July 2025.

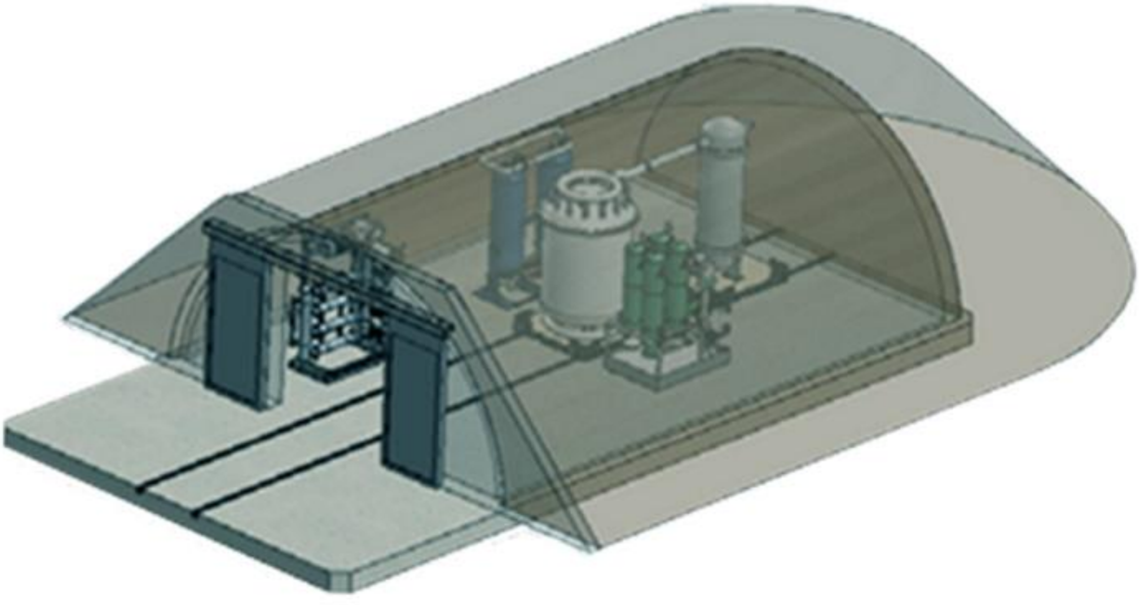


*Image :BWXT BANR*

In March 2020 the US Department of Defence (DOD) awarded contracts, under Project Pele, to three companies, including BWXT, to begin design work on a mobile microreactor prototype. The DOD uses around 30 TWh/year of electricity and 10 million gallons of fuel per day.

The entire reactor system is designed to be assembled on-site and operational within 72 hours. In June 2022, the US Department of Defence awarded a contract to BWXT to complete and deliver the prototype full-scale transportable microreactor by 2024 at the Idaho National Laboratory (INL) site for testing. The fuelled reactor is scheduled to be operating in 2025.

## 6.4 Aurora Powerhouse Oklo (USA)

Oklo is a 4 MWt/1.5 MWe sodium cooled fast reactor, based on the US EBR II reactor that operated for thirty years. The primary cooling system uses heat pipes to transport heat from the metal fuel in the reactor core to a supercritical carbon dioxide power conversion system to generate electricity.

Oklo began formal pre-application engagement with the NRC in 2016.[2] In 2020, Oklo submitted the first ever advanced fission licence application to construct and operate (Combined licence under 10 CFR Part 52) a plant up to 15 MWe.

In 2019 the US DOE issued Oklo with a site use permit and awarded fuel material for the first plant at Idaho National Laboratory (INL).

In May 2023, Oklo and the Southern Ohio Diversification Initiative (SODI) signed an agreement to host two plants in Southern Ohio, up to 30 MWe and 50 MW heat.

In August 2023, Oklo signed an MOU with Centrus (the US enrichment company) to support deployment of Oklo in Southern Ohio. Oklo would purchase HALEU from the planned Centrus production facility in Piketon, Ohio and Centrus would purchase electricity from the planned Oklo reactors on the Piketon site.

*Aurora Powerhouse Image: Oklo*

## 6.5 Nano Nuclear Energy

Nano Nuclear Energy[3] ,a publicly listed company, is developing ZEUS, a solid-core battery reactor and ODIN, a low pressure coolant reactor using natural convection. Both reactors will use HALEU, are modular and designed to be easily transportable, in standard shipping containers.

[2] https://www.nrc.gov/reactors/new-reactors/advanced/who-were-working-with/licensing-activities/pre-application-activities/okla-aurora-powerhouse.html

[3] https://nanonuclearenergy.com/

*ZEUS microreactor – image Nano Nuclear Energy Inc*

## 6.6 Radiant Industries

Radiant[4] is a company founded in 2019 by former Space X engineers. Radiant has been developing a 1.2 MWe HTGR design (named Kaleidos) using TRISO fuel, helium coolant and a graphite moderator. The power generator, reactor, cooling system and shielding are all packaged in a single shipping container facilitating rapid deployment. The entire container can be shipped back for refuelling every five years. Kaleidos can be refuelled a total of 4 times for a 20-year product lifetime. Radiant is targeting commercial unit production in 2028.

In February 2023, Radiant received a Gateway for Accelerated Innovation in Nuclear (GAIN) award from the US DOE to work with Argonne National Laboratory (ANL) on heat production and removal from their microreactor.

# 7 Cost competitiveness of microreactors

A 2019 report[5] by the Nuclear Energy Institute examined the predicted costs of stationary microreactors in the USA. They found that microreactors can be cost competitive for remote locations such as off-grid communities, mine sites, islands and defence installations.
NEI estimated the cost to generate electricity from the first microreactors will be between USD 0.14/kWh and USD 0.41/kWh. As companies continue to produce microreactors, future costs are estimated to fall to between USD 0.09/kWh and USD 0.33/kWh. The range of costs are due to variations in transport accessibility, site conditions, the technology, the ability to

[4] https://www.radiantnuclear.com/

[5] https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/Report-Cost-Competitiveness-of-Micro-Reactors-for-Remote-Markets.pdf

reduce costs through learning, and the type of owner. NEI estimated the cost of diesel generation to be between USD 0.15/kWh and USD 0.60/kWh. (21-86 Australian c/kWh at 0.7 rate)

A feasibility report[6] prepared by Bruce Power and Westinghouse examined the deployment of the eVinci microreactor in mining and remote communities in Canada. There are over 100 remote communities in the Canadian north consuming about 900 million litres of diesel fuel per year. The Natural Resources Canada SMR roadmap identified 24 mines with demands in the range 5 – 20 MW and about 15 new mines are built per year. Westinghouse estimate the LCOE for an eVinci microreactor as $290/MWh. In Canada, the cost of diesel in remote areas is $310-500 /MWh

A large (1 MW) diesel generator fuel consumption is ~ 0.27 l/kWh[7]. Currently in Australia the wholesale cost of diesel is 180-200 c/litre[8] depending on location. This equates to a diesel generation cost of 48.6 – 54 c/kWh

In addition to the fuel cost, the economic costs of diesel generation would also have to take into account the Operations and Maintenance (O&M) cost and the diesel lifetime. O&M costs per kWh decrease with increasing unit size. For a 1 MW diesel generator, O&M costs are in the range 14-25c/kWh[9].

In Australia, a microreactor will need to compete with the 62 – 79 c/kWh cost of fuel and O&M for a large diesel generator. The eVinci microreactor estimated LCOE is USD290/MWh which at an exchange rate of 0.7 = A$414/MWh = 41.4c/kWh.

**If the estimated LCOE is achieved, then the eVinci microreactor will be very competitive with diesel in off-grid situations in Australia.**

Diesel costs are higher in remote communities as the cost of fuel transportation is significant and in some times of the year can be very difficult. Governments generally subsidise these costs to reduce the economic burden on communities. Also for mining industries, fuel and transport costs are a significant part of production costs.

Deployment of microreactors would enable government subsidies to be reduced and would reduce the electricity costs for industrial users.

Some mine sites only operate for 10 years. A microreactor can be taken away and redeployed on another site.

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[6] https://www.brucepower.com/wp-content/uploads/2021/10/210283A_WestinghouseBPMicroReactor_ExecutiveSummary_R000.pdf?__hstc=253552982.5a4af200646ada7106dcbeb2d2216c7c.1715908649356.1715908649356.1715908649356.1&__hssc=253552982.1.1716082368650&__hsfp=628108955&hsCtaTracking=82b3789e-0ccc-43a2-8656-d0a3acbcae6c%7Ca84e469e-5007-43d4-8f4e-eb5d07de4a84

[7] https://www.generatorsource.com/Diesel_Fuel_Consumption.aspx

[8] https://www.unitedpetroleum.com.au/list-pricing/

[9] https://www.researchgate.net/figure/Operations-and-maintenance-costs-per-kWh-from-calculated-models-and-RCA-data-According_fig2_321687684

# 8 Summary of conclusions

8.1 Microreactors are a reliable, flexible source of electricity generation, independent of the weather.

8.2 Microreactors will be an economic option to replace diesel fuel to supply electricity, heat and other energy needs for remote communities, islands and mine sites in Australia.

8.3 Microreactors reduce carbon emissions. There are no emissions during operations and the whole of life emissions are similar to inshore wind and less than solar.

8.4 The deployment of microreactors will reduce the need for government subsidies for diesel for remote communities.

SMR Nuclear Technology Pty Ltd (SMR-NT) is an independent Australian-owned specialist consulting company established in 2012.

SMR-NT was established to advise on and facilitate the siting, development and operation of safe nuclear power generation technologies.

Questions about this report may be directed to:

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